PREDICTIVE MAINTENANCE AND LOGISTICS
(PML)

Richard G. Salter

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ABSTRACT

This paper presents the author's contention that a continuation of the current time-based failure data policies, by all branches of the military, forecloses prospects for substantial improvement in predictive maintenance and logistics (PML).

A concept is proposed for a stress-based data system that promises an affordable and precise prognostic capability for substantial improvements in combat readiness and logistics costs. The concept, Geriometry, evolved during a DARPA-sponsored Rand study of the potential for the application of new technology in the maintenance of Army ground vehicles, in the late 1970s.

A proof-of-principle experiment in one or more operating organizational units is necessary to reduce technical uncertainties, as a first step in piercing the "fog of peace."[1]

INTRODUCTION

The "holy grail" of logistics management is the precise capability to predict the useful life of maintainable or replaceable system components. The benefit of this precision is to effect (1) more efficient maintenance management, with fewer in-service failures, and more complete utilization of the inherent life of all components, and (2) more efficient logistics management, with better prediction of spare parts, personnel and facility requirements.

Classically, predictive maintenance and logistics (PML) is attempted through the use of the failure and maintenance statistical metrics: mean time between failures, MTBF, and mean time to repair, MTTR. These metrics are measured in terms of a "clocking parameter" such as calendar time, operating time, sorties or mileage. In addition, much effort has been, and is being, expended in an attempt to include the biasing effects of other variables on the MTBF and MTTR. An example is the ongoing Rand Project Air Force work wherein the factor of flying hour rate is proposed for biasing the "break rate" for Air Force aircraft. Such biasing is inherently constrained by the extent and precision with which such factors are present in the existing data base, and can be predicted for future operations.

An extensive survey of Army failure and maintenance data collection programs and results was performed by Rand under DARPA contract.[2] It was discovered that, in spite of the progression of programs aimed at improving the quality and utility of maintenance data (TAERS, TAMMS, SAMS, and SDC), "no one knows with any certainty what it currently costs (or should cost) to maintain the various types of Army land vehicles."

In the intervening years, some improvements are manifest in the data collection processes of all the services. However, fundamental problems continue throughout all such data systems. These problems have to do with the nature of the data, apart from the collection processes, and with the recording procedures used. A first concern is that most of the data are "effectual" as opposed to "causal." That is, the *effect* of the stresses in the equipment's

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environment are recorded (e.g. MTBF or wear rate) but the pattern of operating stresses that *caused* these effects is usually known only in gross, aggregate terms, if indeed they are known at all. A second, and related, concern is that the data are essentially snap-shot in nature; that is, the recording is intermittent and the time-resolution is very gross as compared with the time-rate of changes in component stress patterns. Data are recorded by the sortie, or even at shorter time intervals, but seldom continuously. These concerns are true even in most approaches to electronic recording of trend information, a latter day staple of diagnostic information.

To fabricate a hypothetical example for the Air Force flying hours case, flying hour rates are shown to be a factor affecting MTBF, but *there are no data* that would reveal that one squadron contains a number of ex-aerobatic demonstration pilots with a proclivity to throttle bursting in the course of their missions. This practice causes thermal cycling stresses that could reduce turbine shroud life by a factor of three. Without high resolution recording of the proper data and data format, that factor will never be available for projecting the squadron's maintenance plan, the requirements for spare parts or for implementing corrective operational management practices.

Efforts to find better modeling techniques should continue, but should be supplemented with a search for a new data collection and management system based on causal factors. A candidate approach is described below.

GERIOMETRY

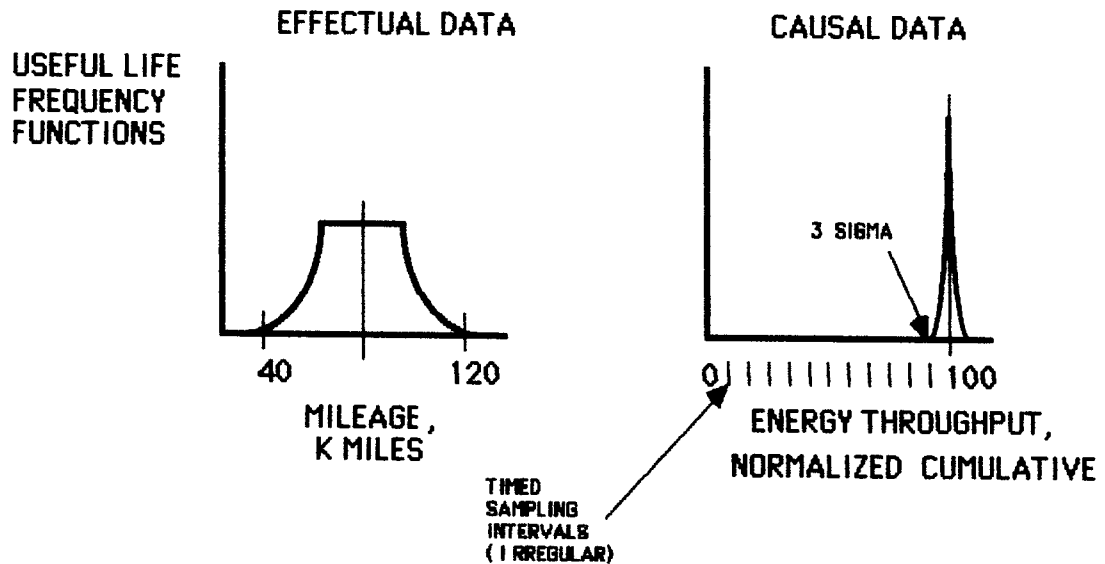Let me begin by making several assertions:

1. There is no such thing as a **random failure**; all failures result from a **deterministic** accumulation of stress damage. This does not deny that failures can occur as the result of chance catastrophic stresses.

2. If the right stress **algorithms** are computed cumulatively, anticipatory maintenance can be effective in maximizing system mission availability while minimizing maintenance costs, and improving percentages in both factors by decades. Algorithms can be engineered for any subsystem or key component, using measurement **proxies** for key stresses in the areas of energy throughput, thermal cycling, and component kinetics. These **Geriometric parameters** become the new "clocking parameters" for measuring MTBF.

3. The **Geriometer** in most system applications can be essentially a **virtual device** in that sensed data will be drawn piggy-back from existing control system sensors with the computations being performed by existing control processors. Computational throughput and memory requirements are quite modest. The Geriometer marginal costs should be small to negligible.

4. **Intelligent logistic system management,** employing the Geriometric data, can be based on computation, data filter, and expert system technology that are well within the current state of the art.

5. A low cost **proof-of-principle** experimental demonstration can and should be accomplished on a **non-interference** basis with an active duty unit of any service branch (there would be synergistic benefits to multi-service experiments). An experiment should encompass a minimum of ten system overhaul life-cycles and would take two to three years, depending on the units' activity levels.

EFFECTUAL DATA   CAUSAL DATA

USEFUL LIFE
FREQUENCY
FUNCTIONS

3 SIGMA

40   120

MILEAGE,
K MILES

0 | | | | | | | | | | | 100

ENERGY THROUGHPUT,
NORMALIZED CUMULATIVE

TIMED
SAMPLING
INTERVALS
(IRREGULAR)

Discussion:

I will develop these assertions further with the aid of the above figure describing General Motors Corp. brake life data.[3]

1. A population of simple physical systems with one dominant failure mode, such as the brake data shown above, wears out or fails in a deterministic manner and will generally be expected to show a pseudo-normally distributed useful life frequency function against either an effectual parameter or a causal parameter. On the other hand, a complex physical system with many independent failure modes, each from different causes and with scattered timing, will tend to exhibit a random failure rate with an exponential useful life frequency function against a simple effectual parameter. These of course are not random failures but rather randomly distributed deterministic failures. If no causal data are collected with which to sort out the individual failure modes, they appear to be random failures because a large number of scattered deterministic distributions taken together give the appearance of randomness.

It is a thesis of Geriometry that all physical components of a system will fail or wear out as a function of the accumulation of damage resulting from the historical pattern of electrical, physical and thermal loads, insults and stresses endured during the course of its

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useful lifetime, and that the useful life will correlate with some cumulative/aggregation of the discriptive parameters in that stress pattern. An obvious analogy can be drawn with fatigue damage and brittle fracture in metals, where the fraction of useful life consumed is proportional to the time integral of the cyclic stress exposure divided by an empirically determined fatigue limit. The thesis extends beyond brittle fracture to include soft parts wearout and ductile failures. The thesis derives from mechanical intuition rather than empirical data. Intuition also suggests that a contribution from the stresses in each of three major sources be combined in accumulating the history for each key failure mode, and that, usually, only one dominant failure mode need be tracked for a given component. The major stress sources are *energy throughput*, *thermal cycling* and *component kinetics*.

2. A Geriometric algorithm will be engineered through failure mechanics analogies for the dominant component failure mode, considering measurement proxies for stresses from the three major sources noted above. Empirical refinement of the algorithm will use data recorded during normal operational deployments. The objective of this refinement will be to reduce the histogram variance as compared with the expected value, on a "useful life" scale in units of the algorithm parameter. An example of the effect can be seen in the GM brake data shown in the figure above. In this case, the algorithm was simply a summation of the energy absorbed by the brakes and is used as the plotting variable for the wearout life histogram. In this example, three sigma of the histogram is approximately four percent of the expected brake life; this allows a maintenance decision criterion at 96% of this expected life. Such a criterion would reduce the probability of in-service failure (with concurrent secondary damage) to a few percent, while utilizing 96% of the expected life, all while obviating all physical inspection procedures. A simple algorithm for this example would be the integration of the vehicle decelerations, as derived from the second derivative with respect to time (using the microcomputer clock) of the distance traveled (using the odometer output). For a cargo vehicle, a load sensor would also be required.

An example of a more complex algorithm for the mechanicals of a reciprocating engine is described in reference 3, page 41. In this case,

a linear function of torque derived from exhaust gas temperature, a squared function of engine speed, and a cubed function of coolant temperature represent the three stress sources, energy throughput, component kinetics, and thermal cycling respectively. These functions are used as weighting factors on each engine revolution, and this product, in turn, is summed over the life of the engine.

Empirical refinement of algorithms can be expedited by simultaneously computing and accumulating several algorithm formulations. The best formulation will yield the histogram with the smallest variance to expected value ratio. Most algorithms will take the form of polynomials and different formulations would use different values for, and combinations of, coefficients and exponents. A single microprocessor-based Geriometer should be capable of clocking a dozen versions of each of a dozen different component algorithms at once, with a sampling resolution of the order of one second.

3. The marginal implementation costs for production Geriometers in most modern military equipment should be low to negligible.
The Geriometer can take a virtual form as a multitasking software implementation in the existing control computer, using the output of instrumentation already connected to that computer. Since the change rates of most source variables are somewhat lethargic, algorithm cycle times of the order of one second, even considering the usual requirement for the computation of multiple algorithms for complex systems, will require only a modest computational throughput and truly insignificant data recording memory. Even in equipment without embedded computers, the costs for a stand-alone Geriometer complete with sensors and harness should be quite nominal, perhaps $250 in commercial parts with a suitable multiplier to accommodate milspec requirements and packaging.

4. The Geriometric clocking parameter will have complex units, with each parameter having its own unique set. Interpretation of these units, in and of themselves, will be meaningless, excepting as they relate to the expected value of the useful life in common terms.
Thus the units will be normalized to the value of the expected life which will represent a figure of 100. Progressing values of the parameter will then relate to a percentage of the useful life consumed.

Since maintenance and logistic planning are done in the calendar time domain, it will be necessary to track the Geriometer's progression in the time domain and estimate the time for overhaul or other service function. This can be done by taking a periodic "reading" of the cumulative value of the parameter versus time and predicting the service date from the "filtered" data string. A considerably simpler filter than the Kalman will suffice to reduce the noise in the data stream. The timed sampling intervals shown in the figure are not meant to imply that any regularity in the timing of the sampling or in the value increment of the sample is required. In most practical circumstances a readout of the Geriometer algorithms would be uploaded to a management computer at refueling or sortie turnaround intervals, which would vary in both time and parameter increment.

On a given system, the Geriometer would maintain algorithm accounts for all key components and subsystems. In some cases the same algorithm is appropriate for more than one component, although the maintenance criterion (the normalization figure) might be different. In other cases, different algorithms are necessary. It is anticipated that in many cases one Geriometer will handle the entire system. The data from the Geriometer can be read into an organizational planning computer by direct connection or by data link. The software in this computer would maintain all necessary maintenance, replacement and Geriometric data histories for all the components of all the systems belonging to the organization, and would flag the immediate maintenance requirements, develop maintenance scheduling for the near term, and make system/mission assignments for pending operations. It would have the necessary embedded expertise to project the unit's logistic requirements against given future mission contingencies. These requirements would be transmitted to the cognizant logistics coordinating organization.

5. The reader will undoubtedly note the profusion of assertions, derived from intuitive engineering, throughout the course of this paper on Geriometry. There is a paucity of cumulative data using appropriate stress algorithms in existence since no motivation for such data has been previously perceived. The GM data resulted from an accidental collection during an attempt to prove that mileage data

is an inappropriate basis for warranting automobile brakes.

It is thus necessary to engage in a proof-of-principle experiment. This experiment should be conducted with an active unit operating in the field and can be conducted on a non-interference basis. The experiment would require the use of stand-alone Geriometers, although some piggy-backing of sensor data might be possible. Initial engineering and programming of brassboard systems and their installation would require six to nine months. Data collection and analyses should encompass at least ten complete overhaul life cycles which would be expected to take from one to two years.

If my intuitions are correct, Geriometry could provide the bridge to truly precise prognostic maintenance and logistics management with all the attendant benefits, including high sortie generation and mission readiness. The fundamental failure precepts are consistent with those embedded in the new avionics design philosophy espoused by the USAF Aeronautical Systems Division.[4] In fact, Geriometry, as the monitoring technology, and ASD's new design philosophy could be highly synergistic.

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